

Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.

# SOIL WATER USE BY APPLE TREES

A thesis presented in partial fulfillment  
of the requirements for  
the Master of Agricultural Science  
in Soil Science at  
Massey University  
New Zealand

Pudjo RAHARDJO

1989

## A B S T R A C T

### SOIL WATER USE BY APPLE TREES

The study investigated the soil water use of an unirrigated tree and an irrigated apple tree in Hawke's Bay, New Zealand in the middle of the summer of 1988/1989. A rainout shelter was used to eliminate any water inputs from both irrigation and rain to the unirrigated tree. The irrigated tree received water inputs from both irrigation and rain. The soil water content was measured by neutron probing and time domain reflectometry. The heat pulse technique was used to measure the sap-flow in the apple trunks. Both leaf water pressure potential and stomatal resistance were measured by the pressure chamber and porometer respectively. A measuring cylinder was used to monitor the apple growth during the study.

The results of the water use measurements were that

- the neutron probing and time domain reflectometry showed the soil water use was about 77 litres (4.3 mm) per day taken from 0 - 1900 mm depth around the irrigated tree. However soil water extraction around the unirrigated tree was only 19 litres (1 mm) per day at the beginning of the study, and no water extraction was measured from the top 1900 mm later in the study.
- the heat pulse technique showed that the unirrigated tree extracted slightly more soil water than the irrigated tree. The average sap-flow measured was 66 litres per day. Probably the unirrigated tree extracted much of its water from below 1900 mm depth, or from beyond the covered area.
- the amount of water use by the apple trees was similar to regional evaporation estimates obtained using the Priestley - Taylor formula, when 0.66 fractional canopy cover was assumed.

The water stress monitoring showed that the pressure chamber technique was a more sensitive way to monitor stress than was porometry.

The leaf water pressure potential values showed a significant difference between the irrigated and the unirrigated apple tree during the latter part of the study.

The readily available soil water storage capacity from 0 to 400 mm depth (the most active part of the root zone), from 0 - 1000 mm depth, and from 0 to 1900 mm, was about 36 mm, 89 mm and 170 mm respectively. When there was a lack of available soil water on the soil, the root system was forced to extract soil water from deep in soil profile.

The comparison of apple fruit growth showed that during the last days of the study, the apples on the unirrigated tree grew more slowly than those on the irrigated tree.

A C K N O W L E D G M E N T S

I am greatly indebted to my supervisors, Dr. B.E. Clothier and Dr. D.R. Scotter, who not only provided helpful guidance in this thesis, but also introduced me to Soil Physics.

I express gratitude to the Ministry of External Relations and Trade, New Zealand for financial support, and to the Government of the Republic of Indonesia, who allowed me to study at Massey University, and still paid my salary during the course of the study.

Thanks to Mr. Van Howard for providing the research site, to Mr. James Watt for providing the meteorological data, to Dr. Paul Gandar and Dr. Keith McNaughton for useful discussion, to Mr. John Julian and Mr. Brooke Tynan for helping me to install the rainout shelter, to Ms. Tina Baker for help with some field observations, and to Mr. Mark Roche for assistance with computing.

Acknowledgement is also given to every member of the Department of Soil Science, Massey University, who provided a pleasant atmosphere in which to study.

I am grateful for encouragement given by Soekinah - Doerjat (my parents), Siti Aminah - Isom Saebani (my parents in law), Farida Rahardjo (my wife), and my sons Danang, Ikhlas and Iqbal Rahardjo. Finally, thanks to Dachman, who sent my office salary for 3 years.

## TABLE OF CONTENTS

ABSTRACT .....	i
ACKNOWLEDGEMENTS .....	iii
TABLE OF CONTENTS .....	iv
LIST OF FIGURES .....	viii
LIST OF TABLES .....	xii

## CHAPTER I

### THE WATER BALANCE OF APPLE TREES

1.1. INTRODUCTION .....	1
1.2. THE WATER BALANCE .....	2
1.2.1. WATER INPUTS .....	2
1.2.2. WATER OUTPUTS .....	3
1.3. THE STUDY .....	4

## CHAPTER II

### SITE DETAILS AND METHODOLOGY

2.1. THE SITE .....	5
2.1.1. THE SOIL .....	5
2.1.2. THE ORCHARD .....	6
2.1.3. ROOT DISTRIBUTION .....	6
2.1.4. THE CLIMATE AND WEATHER .....	9
2.1.5. THE RAINOUT SHELTER .....	12
2.1.6. THE EXPERIMENTAL LAYOUT .....	12

2.2. MEASUREMENTS .....	15
2.2.1. SOIL WATER CONTENT MEASUREMENT .....	17
2.2.2. SOIL WATER PRESSURE POTENTIAL MEASUREMENT .....	17
2.2.3. SAP FLOW MEASUREMENT .....	18
2.2.4. STOMATAL RESISTANCE MEASUREMENT .....	18
2.2.5. LEAF WATER PRESSURE POTENTIAL MEASUREMENT .....	18
2.2.6. APPLE FRUIT GROWTH MEASUREMENT .....	18

### CHAPTER III

#### NEUTRON PROBE AND TIME DOMAIN REFLECTOMETER CALIBRATION AND TENSIO METER DESCRIPTION

3.1. NEUTRON PROBE .....	19
3.1.1. THEORY .....	19
3.1.2. METHODOLOGY AND CALIBRATION .....	20
3.2. TIME DOMAIN REFLECTOMETER .....	22
3.2.1. THEORY .....	22
3.2.2. CALIBRATION METHOD .....	27
3.2.3. CALIBRATION RESULTS AND DISCUSSION .....	28
3.2.4. APPLICATIONS .....	33
3.3. TENSIO METER .....	33
3.3.1. THEORY .....	33
3.3.2. TENSIO METER USED IN THIS STUDY .....	35

## CHAPTER IV

### SOIL WATER MEASUREMENTS

4.1. SOIL WATER CONTENT PROFILES .....	36
4.2. SOIL WATER STORAGE .....	39
4.3. SOIL WATER CONTENT CHANGES .....	42
4.4. SOIL WATER USE .....	44
4.5. SOIL WATER PRESSURE POTENTIAL .....	48

## CHAPTER V

### THE ABOVE GROUND MEASUREMENTS

5.1. HEAT PULSE TECHNIQUE .....	50
5.1.1. SAP-FLOW .....	50
5.1.2. THE TECHNIQUE .....	51
5.1.3. INSTRUMENTATION .....	54
5.1.4. RESULTS .....	56
5.2. STOMATAL RESISTANCES .....	59
5.2.1. STOMATA .....	59
5.2.2. THE POROMETER .....	62
5.2.3. RESULTS .....	65
5.3. LEAF WATER POTENTIAL .....	69
5.3.1. WATER POTENTIAL .....	69
5.3.2. THE PRESSURE CHAMBER .....	70
5.3.3. RESULTS .....	72
5.4. APPLE FRUIT VOLUME .....	75
5.4.1. MEASURING CYLINDER TECHNIQUE .....	75
5.4.2. APPLE FRUIT GROWTH .....	75



CHAPTER VI

## DISCUSSION, CONCLUSIONS AND PRACTICAL IMPLICATIONS

6.1. INTRODUCTION .....	80
6.2. EXPERIMENT DURING SUMMER 1987/1988 .....	80
6.3. SOIL DATA .....	81
6.4. PLANT DATA .....	82
6.5. GENERAL DISCUSSION .....	84
6.6. CONCLUSIONS .....	92
6.7. SOME POSSIBLE PRACTICAL IMPLICATIONS OF THIS STUDY ...	93
6.7.1. THE TYPICAL WATER USE .....	94
6.7.2. THE POSSIBLE SOIL WATER SUPPLY FROM THE WATER TABLE .....	94
6.7.3. THE SOIL WATER RESERVOIR .....	95
6.7.4. THE TYPICAL WATER INPUT FROM IRRIGATION .....	98
6.7.5. THE TYPICAL APPLICATION RATE OF IRRIGATION ....	99
6.8. SUGGESTIONS FOR FUTURE WORK .....	101
REFERENCES .....	102
APPENDIX .....	111

# LIST OF FIGURES

2.1.	Apple trees in the orchard during the fruiting period.....	7
2.2.	The average root length density measured with depth for all radii (a) and with depth in various radial classes (b) (K.A. Hughes, pers. comm.).....	8
2.3.	The average monthly rainfall (1959 to 1980) for Station D96689, Havelock North, 9 m above sea level, and average monthly Penmann evaporation for Napier (NZ Met. Service, pers. comm.).....	10
2.4.	The rainout shelter around Tree U, open for measurements....	13
2.5.	The difference between the soil within and outside the covered area around Tree U.....	13
2.6.	The layout of the experimental site in the apple orchard....	14
2.7.	Layout around Tree I (above) and Tree U (bottom).....	16
3.1	(a). The soil water content profile at site 0, as measured gravimetrically on exhumed soil cores, and by neutron probing immediately afterwards.....	21
3.1	(b). The soil water content profile at site 10, as measured gravimetrically on exhumed soil cores, and by neutron probing immediately afterwards.....	21
3.2.	Comparison between the count ratio from the Troxler 1255 probe with the soil water content measured by the Troxler 1255.....	23
3.3.	The factory and new calibration at Site A and Site B.....	24
3.4.	A comparison of results of the TDR experiments on four different soils possessing a wide range of textures with the results of other experiments which used a variety of technique and soils (after Topp et al. 1980).....	26

3.5.	Laboratory TDR calibration sampling and measurement locations.....	27
3.6.	The three TDR instruments and a soil bucket as used in the calibration experiments.....	29
3.7.	The relationships between TDR and corer sampling water content in the laboratory calibration.....	30
3.8.	The laboratory and field calibration of TDR no. 104968 which was used in the experiment.....	32
4.1.	The volumetric soil water content profiles for Tree I measured on Day 1 (.), Day 18 (x) and Day 29 (o). For depth 0 - 400 mm TDR apparatus was used, while for depth 400 - 1800 mm a neutron probe was used.....	37
4.2.	The volumetric soil water content profiles for Tree U measured between on Day 1 (.) and Day 29 (x). For depth 0 - 400 mm TDR apparatus was used, while for depth 400 - 1800 mm a neutron probe was used.....	38
4.3.	Soil water storage from 0 to 1900 mm depth with time for irrigated tree (Sites 1 - 4) and unirrigated tree (Sites 5 - 9), obtained by combining neutron probe and TDR data.....	41
4.4.	Change in soil water content profiles during two extraction periods for irrigated tree, (a) from Day 7 to Day 16 (9 days), (b) from Day 23 to Day 29 (6 days).....	43
4.5.	Change in soil water content profile during two extraction periods for unirrigated tree, (a) from Day 7 to Day 16 (9 days), (b) from Day 23 to Day 29 (6 days).....	45
4.6.	Soil water pressure potential measured by electronic tensiometer around Tree I (a) and around Tree U (b).....	49
5.1	(a). The typical relationship between temperature and time for heat pulses upstream ( $X_u = 5$ mm) and downstream ( $X_d = 10$ mm).....	52

5.1	(b). The typical difference between downstream and upstream temperature. $t_0$ is the time delay until the upstream and downstream temperatures are equal (after Swanson, 1962).....	52
5.2	(a). A diagram showing the position of heater probe and thermistor beads used to monitor the heat pulse velocity.....	55
5.2	(b). Two of three sets of heater probes and thermistor beads in the trunk of Tree U.....	55
5.3	(a). The heat pulse instruments in Tree U, consisting of 3 sets of thermistor beads and heaters (1) which were controlled by heat pulse and heater circuits (2) and connected to a Campbell CR21X data logger (3) powered by a 12 Volts lead-acid battery (4) and connected to an audio cassette recorder (5).....	57
5.3	(b). Data saved by the cassette recorder (5) were transferred by a tape reader (6) to a computer (7).....	57
5.4.	The pattern of daily water use (litres/hour) from Day 2 to Day 24 as measured by the heat pulse technique for Tree I (——) and Tree U (----).....	58
5.5.	Daily water use measured by the heat pulse technique from Day 2 to 24 for Tree I (——) and Tree U (----) .....	60
5.6	(a). The Delta-T Device Porometer.....	63
5.6	(b). Using the porometer to measure the stomatal resistance of the bottom of a leaf.....	63
5.7.	The correlation between diffusion time (s) and plate resistance (s/cm) for porometer calibration under various relative humidity and temperature conditions.....	64
5.8.	Stomatal resistance of apple leaves from Trees I and U. Days 14, 16 and 15 showed a significant difference (indicated with *) in the stomatal resistance values between Trees I and U.....	66

5.9.	Diagram of the pressure chamber apparatus.....	71
5.10.	The pressure chamber apparatus used in the research.....	71
5.11.	Leaf water potential measured by pressure chamber apparatus on Days 8 to 30. The first and second numbers in the parenthes show the number of leaf samples of Trees I and U respectively being measured.....	73
5.12.	The measuring cylinder used to monitor apple growth.....	76
5.13.	The relationship between apple fruit volume (ml) and time (days) for Tree I (above) and Tree U (below).....	77
5.14.	The average apple fruit volume with time.....	78
6.1.	Soil water extraction from 0 - 1100 mm and 1100 - 1900 mm depth around Trees I and U during the first and second period of extractions.....	83
6.2.	Water use per tree measured by heat pulse technique and regional evaporation of Priestley and Taylor method.....	85
6.3.	The comparison between water use per tree measured by neutron probe (assuming full root distribution), heat pulse technique and regional evaporation of Priestley and Taylor method (assuming 66 percent canopy cover).....	87
6.4.	The relationship between the Priestley and Taylor estimates and the heat pulse measurements.....	89
6.5.	The average "field capacity" and "stress point".....	90
6.6.	The relationship between meteorological data to the stomatal resistance and leaf water potential.....	97
6.7.	The wetting hydraulic conductivity, $K(\phi)$ , of Twyford sand loam from three cores, with disc and ring measurements for varying $\phi_0$ (after Clothier et al., 1989).....	100

# L I S T   O F   T A B L E S

2.1.	Meteorological data for Havelock North (Station no. D 9668A) from 13 December 1988 to 10 January 1989 (supplied by NZ Meteorological Service).....	11
3.1.	The relationships between volumetric soil water contents from TDR using factory calibration (Y) and gravimetric sampling (X).....	28
4.1.	Soil water storage change per unit land area during extraction periods.....	47
4.2.	Soil water storage change per tree.....	47
5.1.	The diffusion resistance and time correction.....	67
5.2.	Average and standard deviations of stomatal resistance (s/cm) values and t-test parameter.....	68
5.3.	Average leaf water pressure potential (MPa).....	74
5.4.	The average of apple fruit growth rate (ml/day) of both Trees I and U.....	79

## CHAPTER I

### THE WATER BALANCE OF APPLE TREES

#### 1.1. INTRODUCTION

Fruit and vegetables are in the top six New Zealand exports, after meat, wool, butter, forest products, and aluminium and alloys. The value of fruit and vegetables is about 7 percent of the national export receipts. Apples are the second most important commodity in the fruit export sector after kiwifruit (HEDC, 1982). The national apple production is about 155 million tonnes/annum (Wong, 1987). Thus apples are an important New Zealand export commodity.

Apple orchards usually use irrigation systems to overcome soil water deficits during dry periods when evaporation is greater than rainfall, and so to obtain the maximum yield and fruit quality. Using an irrigation system involves defining when and how the optimal amount of water should be applied in an orchard. Otherwise the orchard will receive either over-irrigation or under-irrigation. Over-irrigation has several disadvantages, namely :

- higher irrigation expenses,
- nutrient leaching which can affect ground water quality and increase fertiliser cost,
- plant health problems due to water logging,
- decreased yield and fruit quality

On the other hand, under-irrigation causes plants to become unhealthy due to water stress and low soil nutrient availability. Thus it is important to investigate the amount of irrigation needed.

Irrigation is a water input, which is a component of the water balance. The understanding of the balance of the water inputs and outputs in an apple orchard is very important, because an unfavorable water balance can affect the apple tree development which can affect the export quantity and quality.

## 1.2. THE WATER BALANCE

Mass conservation can be used to explain the soil water balance (Hillel, 1982). In the root zone of an orchard over any time interval  $\Delta t$ , the change in storage equals the water inputs minus the outputs.

The inputs are rainfall (R) and irrigation (I), and the outputs are evaporation (E), drainage below the root zone (D) and surface runoff (S). In this thesis evaporation refers to all water vapour loss to the atmosphere, and so includes transpiration, evaporation from the soil and evaporation of intercepted water. So

$$\Delta W = R + I - E - D - S \quad (1.1)$$

where  $\Delta W$  is the change in the water storage in the root zone, and all terms have dimensions of length, being equivalent depths of water.

### 1.2.1. WATER INPUTS

Water inputs in the orchard are rainfall and irrigation water. Rainfall and irrigation are treated as independent variables and must be measured (Scotter et al., 1979). When water inputs bring the soil to "field capacity", then the soil water deficit is assumed to be zero (Taylor and Ashcroft, 1972). Excess water input leads to water redistribution and drainage beyond the root zone. But drainage losses during summer will be small if the irrigation system is well managed.

In orchards infiltration with water ponded on the surface is rare. It usually only occurs during heavy rain and on less permeable soils. Most of the water falling on the land, as either rain or sprinkler irrigation, infiltrates as unsaturated flow (Philip, 1969).



#### 1.2.2. WATER OUTPUTS

Given no surface runoff, the water outputs in the orchard are evaporation, and drainage water, which only occurs when there is excess water input. The understanding of evaporation is very important in agriculture and horticulture because evaporation is a major term in the soil water balance.

When the humidity in the atmosphere outside the leaf cuticle is lower than in the intercellular spaces within a leaf, there is molecular diffusion of vapour outwards through the stomata. The number and degree of opening of the stomata, and the humidity gradient control the rate of diffusion. The continual transpiration from leaves needs three physical conditions. Firstly, a supply of energy must be available to provide the quite large latent heat of vaporation. Secondly, there must be a lower vapour pressure in the surrounding air than at the evaporating surface. Thirdly, there must be a continuous supply of water. This is the rate limiting factor for transpiration in dry condition (Rose, 1966; Meidner and Sherif, 1976; Milburn, 1979).

Transpiration from plant leaves causes a water potential gradient between leaves and roots. The root water absorption and sap flow depend not only on the leaf water potential, but also on the soil water potential and hydraulic conductivity. On the other hand, the atmospheric environment largely determines the rate of evaporation from the leaves, because the opening of stomata depends on environmental variables such as the solar radiation received, and the humidity gradient between inside and outside the stomata. Thus, the whole soil-plant-atmosphere continuum affects the amount of water lost by evaporation (Philip, 1966). Often however the atmosphere has the dominant effect on the rate of evaporation as the process is usually energy limited.

When evaporation from bare soil can be ignored, such as in a region which is completely covered by vegetation, and soil water is always available, the root water extraction rate can be assumed to be equal to the evaporation rate. Then, provided adequate soil water is available, estimates of regional evaporation using climate data can be used to estimate root water extraction (Thornthwaite, 1948; Blaney and Criddle, 1950, Penman, 1948, Priestley and Taylor, 1972). The actual evaporation is usually measured only for research purposes.

### 1.3. THE STUDY

The aim of the study was to investigate the soil water use by two apple trees in Hawke's Bay.

One apple tree was covered by a rainout shelter over the soil surface to eliminate any water input from irrigation and rainfall, and to prevent any water output from soil and grass evaporation. Thus transpiration is the only water use around this unirrigated tree.

The other apple tree had no any cover. This tree received water inputs from both irrigation and rainfall. The water use consisted of transpiration and both soil and grass evaporations around the tree.

The water use of both trees was investigated by using

- neutron probing and time domain reflectometry to monitor spatial and temporal soil water content changes, reflecting the root water extraction,
- the heat pulse technique to measure the sap flow in the tree,
- meteorological data to estimate regional evaporation around the orchard.

The unirrigated tree was expected to come under water stress, while the irrigated tree was expected to remain unstressed. To detect the level of plant water stress, a porometer was used to measure the stomatal resistance and a pressure chamber was used to measure the leaf water pressure potential. Soil matric potential was measured with tensiometers. Finally, a measuring cylinder was used to monitor the apple fruit growth on the two apple trees.